Enabling Power at Sea: Opportunities for Expanded Ocean Observations through Marine Renewable Energy Integration

Preprint

Rebecca Green,[1] Andrea Copping,[2] Robert Cavagnaro,[2] Deborah Rose,[2] Dorian Overhus,[2] and Scott Jenne[1]

1 National Renewable Energy Laboratory
2 Pacific Northwest National Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Enabling Power at Sea

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Rebecca Green
National Renewable Energy Laboratory
Golden, CO, USA
rebecca.green@nrel.gov

Andrea Copping
Pacific Northwest National Laboratory
Seattle, WA, USA
andrea.copping@pnnl.gov

Robert J. Cavagnaro
Pacific Northwest National Laboratory
Seattle, WA, USA
robert.cavagnaro@pnnl.gov

Deborah Rose
Pacific Northwest National Laboratory
Seattle, WA, USA
deborah.rose@pnnl.gov

Dorian Overhus
Pacific Northwest National Laboratory
Seattle, WA, USA
dorian.overhus@pnnl.gov

Dale Jenne
National Renewable Energy Laboratory
Golden, CO, USA
dale.jenne@nrel.gov

***Abstract*—The blue economy is a dynamic and rapidly growing movement that captures the interplay between economic, social, and ecological sustainability of the ocean and encompasses numerous maritime sectors and activities (e.g., commerce and trade; living resources; renewable energy; minerals, materials, and freshwater; and ocean health and data). The demand for ocean data to inform scientific, risk reduction, and national security needs is leading to a large increase in the number of deployed ocean observation and monitoring systems, most of which require increased power. Because ocean observation systems are often placed in remote locations, they primarily rely on energy storage (or in some cases in situ energy generation) to power instruments and equipment, which imposes limits on sampling rates, deployment times, and spatiotemporal resolution of data. The U.S. Department of Energy Water Power Technologies Office is exploring the potential for marine renewable energy (MRE) devices (largely wave and tidal energy converters) to provide power to support multiple blue economy opportunities. A portion of these opportunities focus on power at sea markets for providing power in off-grid and offshore locations to support a variety of ocean-based activities, including ocean observation and navigation, underwater vehicle charging, marine aquaculture, marine algae farming, and seawater mining. Initially, research has focused on better understanding how and where MRE can provide a consistent source of reliable power to extend ocean observing missions, including operation of autonomous underwater vehicles. Online surveys as well as phone and in-person interviews were conducted with experts in the field of ocean observing systems and observatories to gather end-user requirements, determine energy needs, identify opportunities for codevelopment, and pinpoint constraints for MRE to meet those needs. The surveys and interviews provided feedback on the potential for powering devices and vehicles using MRE, including identifying common themes and challenges that will inform foundational research and development steps needed to advance the integration of MRE with ocean observing systems. In most cases, additional power generation on the order of watts was identified as significantly beneficial to enhancing ocean observations capabilities.**

***Index Terms*—marine renewable energy; blue economy; ocean observations; power requirements**

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I. Introduction

The desire to develop technologies with minimal carbon impact and to promote long-term economic sustainability has included early-stage development of marine renewable energy (MRE), largely from tidal and wave resources [1]. Initial MRE development has focused on the goal of providing energy from the ocean to the national electricity grids of participating nations, including the United States. More recently it has been recognized that the emergence of maritime industries and other uses in the blue economy have provided promising opportunities for MRE that are cost competitive with other renewable energy sources [2]. In particular, supplying power at sea in locations where local sources of energy are either sparse or have not been deemed economically viable has become the focus of programs that seek to link the power needs of mobile and stationary ocean observation platforms with energy generation from MRE.

Under the direction of the U.S. Department of Energy (DOE) Water Power Technologies Office, an extensive study was undertaken to identify promising applications for MRE. The resulting Powering the Blue Economy report explored opportunities for MRE across a range of maritime markets [3]. Based on available information, the interest of federal and regional partners, and promising colocation of energy resources at sea with specific end uses, a connection between MRE and ocean observations, including underwater recharge of autonomous underwater vehicles (AUVs), was identified for further investigation and development.

Buoys, floats, surface and subsurface autonomous vehicles, gliders, profiling moorings, and seabed observatories all play a part in ocean observation systems around the world. With some exception for the instruments and installations associated with cabled arrays, all operate under constraints of power and in many cases, limited data communication. Permanent or semipermanent observation platforms on the sea surface often rely on solar panels and occasionally wind turbines for power; this constrains the range of sensors and duty cycles able to be deployed, particularly in high latitudes and during winter months in temperate areas. Vehicles and moorings that operate subsurface are entirely constrained by battery power and require surface ships to retrieve or visit the installations on a routine basis. Autonomous surface vehicles that harvest wave or wind energy for propulsion are also available for ocean monitoring [4], [5].

MRE encompasses the harvest of energy from the movement of ocean waters in the form of either currents or waves, as well as from other energy sources. To date, this has most commonly been achieved with turbines in tidal channels, from ocean currents, and rivers, as well as the utilization of wave energy converters of many designs and depths in wave fields. MRE also includes the harvest of energy from temperature differentials in warm tropical and subtropical waters, in the form of ocean thermal energy conversion (OTEC), as well as energy generation from salinity differentials. Each of these technologies has unique attributes, making it difficult to converge on one MRE technology. The varying technologies are likely to have benefits in different applications because of their unique operating principles. Within each subcategory of MRE, there have been significant variances to these attributes, creating a wide range of potential solutions (Fig.1).

To date, specific needs of the ocean observations community related to energy limitations and opportunities enabled by marine energy system integration have not been investigated or quantified. We aim to demonstrate the potential for development of marine-energy-powered ocean sensing through analysis and reporting of information gathered from experts in this community.

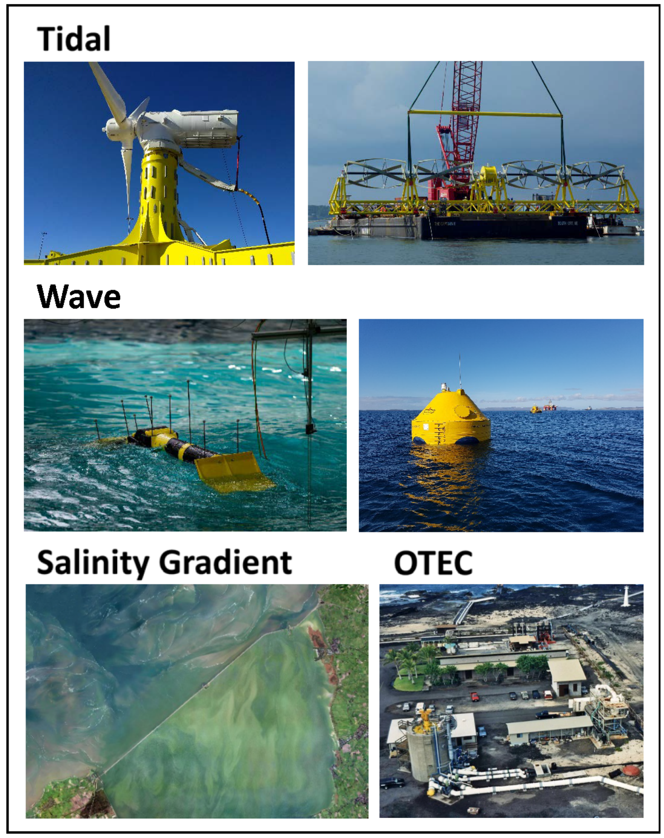

Fig. 1. Sampling of designs used for marine energy devices and concepts, including tidal, wave, salinity gradient, and thermal gradient power systems. Pictured examples include (from top left to bottom right): ANDRITZ Hydro tidal turbine, ORPC TidGen Power System, Mocean Energy Blue Horizon attenuator, CorPower Ocean C3 point absorber, REDstack salinity gradient plant at Afsluitdijk (photo courtesy of Van Oord), Natural Energy Laboratory of Hawaii Authority OTEC plant at Kona (photo courtesy of DOE). All wave and tidal images were received from developers with permission for third-party use.

II. Methods

Information on specific power and data communication needs for ocean observation sensors and underwater vehicles was collected from ocean observation experts representing a range of scientific, commercial, and military/homeland security uses. Two methods were used for gathering information. The first was a structured online survey (SurveyMonkey tool) that was sent to 143 contacts with a request to pass it on to colleagues. Second, key individuals were asked to participate in structured telephone or in-person interviews lasting 30 to 60 minutes. The individuals for both the surveys and interviews were chosen from among those known to be prominent in the fields and through a Delphi approach, requesting additional contacts from those interviewed. The survey questions focused on ocean observation mission impacts, energy needs and limitations of platforms and vehicles, and potential opportunities for use of MRE to power future missions. The interview questions dove deeper into the same material, with the ability for the interviewers to follow up with the experts to elicit additional information. In many cases, the interviews also informed the ocean observation experts of the intent of DOE to pursue MRE as a power source in the blue economy, and to enlist their interest and support for future partnership possibilities.

III. Results

A. *Ocean Observation Mission Impacts*

Information gathered as part of this study detailed how ocean observations from remote and in situ marine sensing platforms are a critical component of monitoring and detecting changes in the ocean with applications across multiple sectors, including scientific and oceanographic research, military and homeland security, and commercial applications. Feedback was gathered from 68 expert responses, including 41 SurveyMonkey responses and 27 telephone or in-person interviews. A range of perspectives was provided by academic, government, and industry experts from across U.S. oceanic and Great Lakes regions covered by the current ocean observing network, which spans a range of marine energy regimes (Fig. 2). Each region was represented in the surveys and interviews as follows, with some respondents identifying multiple regions of interest (number of respondents in parentheses): Pacific (25), Atlantic (15), Gulf of Mexico (9), Alaska/Arctic (8), Great Lakes (3), and international waters (19).

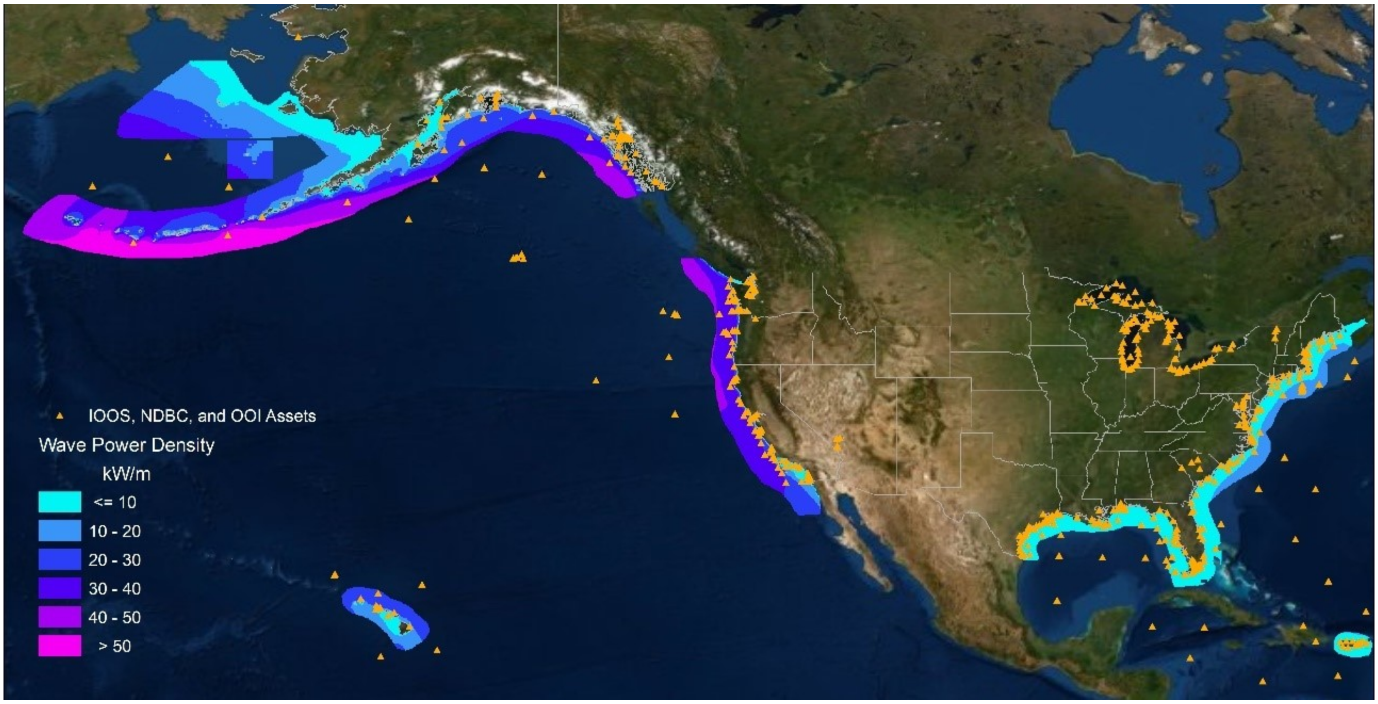

Fig. 2. Interviews broadly spanned the regional diversity of ocean observing systems and marine energy resources, as exemplified here by a subset of observing assets and wave resources.

The interviews gathered feedback across existing and emerging ocean observing systems in U.S. waters, including the Integrated Ocean Observing System (IOOS) and its network of partner assets. The IOOS program strives to use ocean observations to significantly improve the nations ability to achieve specific societal goals, ranging from improving predictions of climate change and weather to enabling the sustained use of ocean and coastal resources, including for commercial and recreational fishing [6]. Interviewees from academia, IOOS, and the National Oceanic and Atmospheric Administration (NOAA, the lead agency for IOOS) emphasized the use of ocean observations to further research and provide operational data to improve forecast modeling, with special emphasis on providing data sets needed (i.e., sea surface temperature, wind speed, ocean currents, and so on) to inform weather and hurricane forecasting around the country to reduce disaster-related loss of life and property.

Interviews were also conducted with experts performing more basic scientific research as a part of the National Science Foundation-funded Ocean Observatories Initiative (OOI), which is another key component of the existing network of ocean observing systems in the United States. The OOI program is a networked infrastructure of science-driven sensor systems that measures physical, chemical, geological, and biological variables in the ocean, seafloor, and overlying atmosphere, with arrays and nodes located off Massachusetts, Oregon, Washington, Hawaii, Argentina, Greenland, and Chile. Interviewees discussed the various science themes and locations represented by the OOI program and drew clear connections between their collection of basic scientific data and relevance to applied themes, such as hurricane forecasting, tsunami detection, and fisheries management.

The commercial sector provided unique perspectives on the supply of marine sensing devices and vehicles that contribute to the ocean economy and end-use applications. According to NOAA's Ocean Enterprise Study, providers of ocean observing infrastructure and intermediaries that make use of ocean data collectively amount to approximately 400 businesses in the United States and collect approximately $7 billion in annual revenues [7]. We interviewed several of these companies in person at the 2019 Blue Tech Expo and through follow-up phone interviews. The oil and gas industry was commonly identified as a major customer for ocean observations, with marine measurements informing risk reduction and monitoring, structural design for extreme conditions, generating data for safe offshore operations, and the economics of design/selection of offshore structures. One goal is to develop seafloor resident AUVs and subsurface moorings for the oil and gas market in deep water, with the need for accurate observations increasing with depth. Broadly, companies indicated the need for providing a variety of sensors and platforms (AUVs, remotely operated vehicles [ROVs], gliders, and moorings) to perform environmental monitoring, inspections, and scientific missions for offshore industries, U.S. federal government agencies (e.g., NOAA, Navy, Coast Guard), and university researchers.

Several interviewees from the research and commercial sectors shared perspectives on the importance of ocean observing systems to the Department of Defense and Department of Homeland Security to inform military, emergency response, and national security activities, including those of the U.S. Navy and Coast Guard. For example, the Naval Oceanographic Office maintains the world's largest fleet of underwater gliders that are imperative to a wide range of naval operations and have numerous applications, from diver safety to detection of submarines to hurricane prediction. The Navy is funding development of long-duration unmanned underwater vehicles to maintain a constant naval presence for dynamic maritime awareness. The Coast Guard relies on the use of a suite of ocean observing data to inform search, rescue, and emergency response capabilities in offshore and remote locations, including use of drifting buoys and high-frequency radar. Other ocean observing applications described by interviewees included harbor monitoring/security, mine sweeping, and 3-D seafloor (bathymetry) mapping by sonar.

B. Energy Needs and Limitations

Decades of development of oceanographic sensors and platforms under traditional power constraints has resulted in technologies capable of operating effectively while using very little energy. Similarly, systems can generally be configured to run on duty cycles or specified sampling intervals, extending mission duration at the expense of finer temporal resolution. Interviewees and survey respondents were asked to list and discuss the types of sensors and platforms they use for ocean observations to help quantify the range of power requirements across the community. For the following analysis, sensors are defined as discrete devices, while platforms are systems consisting of one or more devices and hardware to keep station or enable mobility. Thirty-one types of sensors and fourteen platforms were listed or described. Power requirements for specifically named devices were compiled from manufacturers specifications, while typical examples were used for those discussed in more general terms.

Operational power draw for oceanographic sensors spans roughly six orders of magnitude from milliwatts to hundreds of watts. In order of increasing power draw, about a quarter (26%) of the surveyed sensors run on less than 1 W, nearly half (48%) run on 1-10 W, 19% require 10-100 W, and the remaining sensors (7%) use more than 100 W. Sensors were further grouped into categories by common measurement attributes, including physical oceanographic, passive acoustics, cameras and wipers, communication and navigation, biological oceanographic, and active acoustics. The power requirements for each sensor category were averaged to show the range of power needs across sensor types (Fig. 3).

Oceanographic platform power requirements range from approximately 10 milliwatts to more than a kilowatt. Platforms consisting of multiple sensors may report average power use lower than the sum of the operational power of their sensors because of using duty cycles and averaging over long periods of time. In addition to sensors, averages of power for categories of platforms were determined (Fig. 3). Platforms measuring physical oceanographic properties with multiyear missions have been engineered to use the least power, such as drifting profiling floats, which use 0.1 W. By contrast, hybrid AUV-ROV systems engineered for speed, manipulation of subsea objects, and large payloads use the most power (up to 1.3 kW).

Responses to a question asking for a description of the limitations to current ocean observing activities were coded into categories representing common themes. Of these, power and batteries were most frequently mentioned (48 comments), followed by data transmission and communications (32 comments), and survivability (9 comments). Examples of other limitations for ocean observations emphasized by interviewees included device reliability, cost of ship time, cost of cables

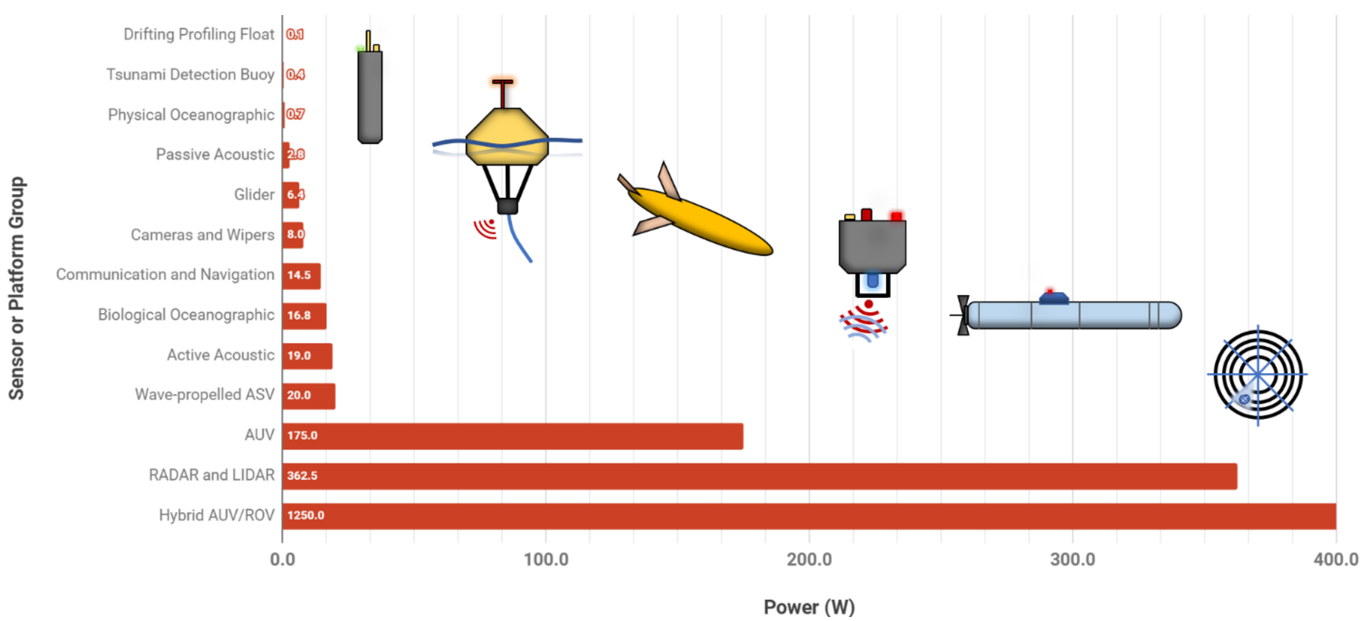

Fig. 3. Operational power requirements for ocean observation sensor and platform categories.

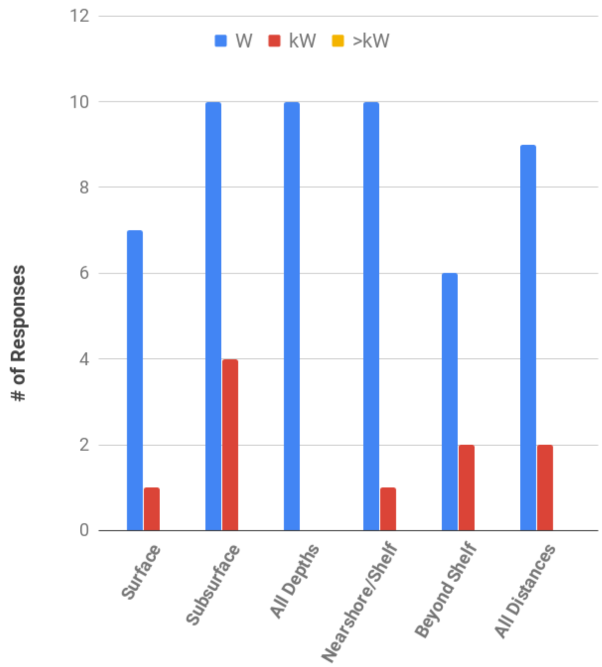

Fig. 4. Reported power range used by depth and distance zones. Note that there were no responses in the “>kW” range.

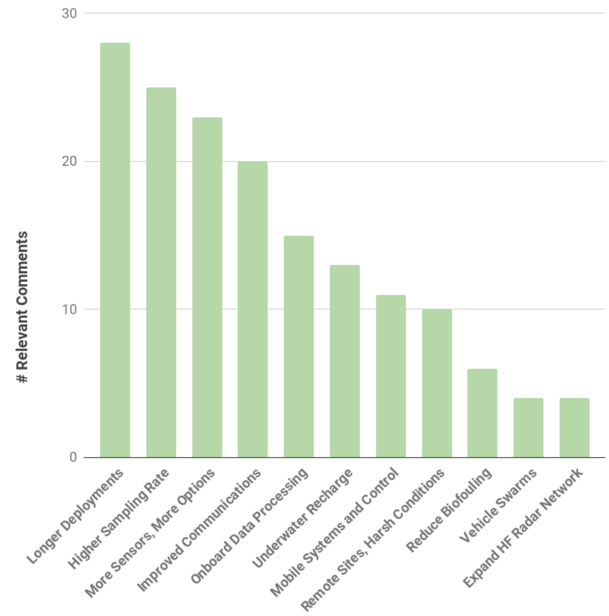

Fig. 5. Responses on enabling ocean observations if more power was available.

for observatories, funding, biofouling, instrument calibration, vandalization of buoys, hazards associated with lithium-ion batteries, onboard processing, and winter ice conditions.

Additionally, the range of power use reported by respondents was organized by corresponding depth and distance from shore. The operational location of sensors and platforms supplied by the respondents was organized by power level as surface, subsurface, nearshore/shelf, and beyond shelf, while some respondents indicated that they work in multiple zones (Fig. 4). Power used is predominately in the watts range across locations, and sometimes kilowatts range, corresponding to the power ranges of the sensors deployed.

C. *Opportunities for Use of Marine Energy*

Limitations and challenges (with power being the chief concern) were identified through the survey and interviews. Those surveyed and interviewed were asked to comment on what they would do in the realm of ocean observations if more power was available. Responses were coded and grouped into themes reflecting the most common responses (Fig. 5). Extending deployment duration, sampling rate, and numbers/types of sensors and platforms were common points of discussion, followed by improved communications and increased onboard data processing, and enhancements specific to mobile systems/vehicles. Several responses represent the highest power applications described, such as the operation of swarms of vehicles and expansion of high-frequency radar arrays.

Themes on increased use of power to enable ocean observations correspond well with responses indicating how much more power is wanted (Fig. 6). Additional power on the order of watts is most commonly desired to enable longer duration missions or higher sampling rates, and to include additional sensors in platforms. A notable exception is those listing beyond shelf (deep ocean) as their primary zone, where most respondents use power on the order of watts but want power on the order of kilowatts. Similarly, some working closer to shore would prefer more than 1 kW of power, such as corresponding to expansion of high-frequency radar arrays. Based on these results, we see great opportunity for coupling or co-designing marine energy systems capable of producing less than 1 kW on average, with sensor platforms operating near the surface, and higher power rated systems for subsea platforms or those directly adjacent to shore.

The high cost of deployment, operation, and maintenance of ocean observations systems is reflected in interview responses. Most interviewees (67%) discussed vessel, fuel, and/or personnel costs – some mentioning these three or more times. Exact costs associated with powering sensors and platforms were difficult to determine from responses. However, many interviewees indicated capital expenses for power systems (e.g., batteries) are dwarfed by costs associated with deployment, maintenance, and recovery. This is congruent with our experience and understanding of the sensor and platform end-user and market space. We recognize that increased power offers an opportunity for expanded use of autonomous systems and extended duration of platform deployment. Incorporation of marine energy may help reduce the overall life cycle cost

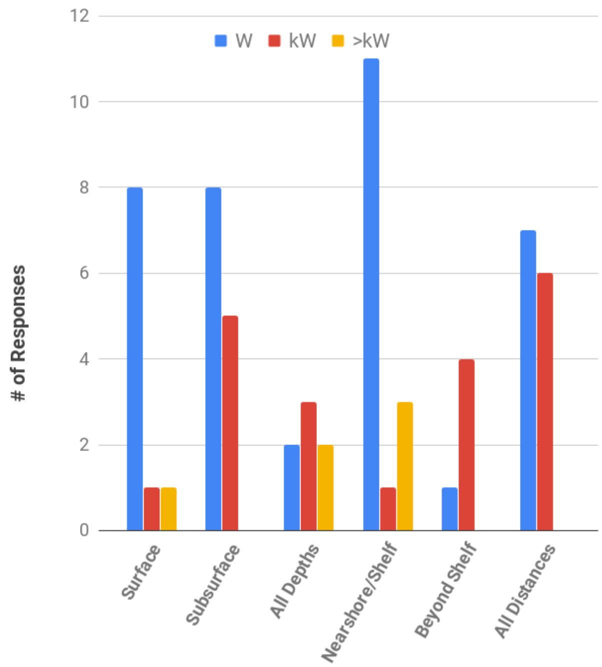

Fig. 6. Reported power range desired by depth and distance zones.

of ocean observations systems.

In addition to providing electricity, interviewees were asked about how mechanical work from MRE might help enable their ocean observing missions. Use of marine energy to directly provide vehicle propulsion was identified by several respondents, such as is done with the Wave Glider and similar vehicles. Additionally, the use of wave energy to physically move instrumentation up and down a mooring line with profiling instrumentation was discussed, similar to how the Wire Walker operates [8]. Numerous respondents also suggested mechanical means for scrubbing or otherwise removing biofouling from devices, as fouling of instrumentation is a concern for many types of oceanographic instrumentation, with direct impacts on operation and maintenance costs.

IV. Discussion and Next Steps

Our assessment of survey and interview results indicates a compelling value proposition for the integration of MRE with oceanographic research, national security, and commercial missions. These missions will increasingly rely on autonomous sensors, unmanned vehicles, and new approaches to onboard energy generation, storage, and reliable remote recharging. For example, operators of buoy networks indicated that the ability to provide tens to hundreds of watts to their systems would strongly enable expanding sensor payloads and continuous operation throughout the year, especially in winter months and at high latitudes. Operators of AUVs expressed that larger amounts of power, hundreds of watts to kilowatts, would enable a step change in future resident AUV missions by enabling underwater recharging and operation of larger numbers of vehicles. Geographically, investigators from all U.S. regions (i.e., Atlantic, Gulf of Mexico, Pacific, Alaska, and Great Lakes) expressed a desire for greater amounts of power to expand ocean observing missions, as well as requests for greater amounts of power to serve missions in deeper oceanic regions and at high latitudes (e.g., under ice sheets) to support a sustained underwater vehicle presence.

Common themes and challenges identified through the surveys and interviews will inform the next foundational research and development steps needed to advance the integration of MRE with ocean observing systems to better achieve mission goals, such as higher sampling rates, longer deployment times, and greater spatial and temporal data resolution. While various MRE technologies have been developed over the years [9], most are focused on utility-scale opportunities for power generation and are not necessarily suited to the unique (and typically much smaller) power requirements of ocean observing systems, as identified by end users in our surveys. The majority of interviewees were welcoming of future opportunities to explore integration of marine energy with the ocean observing systems they operate and volunteered their platforms as test beds for such integration. Future research will explore specific end-use cases within ocean observing for marine energy integration and work toward developing design requirements based on identified end-user needs.

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